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A method for the determination of the critical current for a conductor including superconducting material, and an apparatus for performing the method

The invention relates to the determination of the critical current for a conductor including superconducting material, and to an apparatus for performing the method.

5 Conductors comprising superconducting material have different uses, e.g. in connection with magnets, transformers, and as conductors for electrical power distribution. Superconducting material is advantageously used in conductors as the superconducting material can be brought
10 into a superconducting state enabling electrical energy to be transmitted with little energy loss. Reduced electrical power loss is also advantageous as it enables construction of e.g. transformers, magnets, and conductors with smaller dimensions compared to the use of conven-
15 tional conductors.

Conductors comprising superconducting material can be constructed as a single core conductor, but is often constructed as a number of filaments arranged to form a
20 multi-core conductor.

When a superconductor is brought into the superconduction state, e.g. by cooling, electrical power can be transmitted with little loss, as long as the current is lower than the so-called critical current. The critical cur-
25 rent, i.e. that current which the superconductor material is able to support without going into a normally conductive state, is a characteristic value of the given superconductor. It is of great importance to determine
30 the critical current for a conductor comprising superconducting material, as the value of the critical current is needed when dimensioning e.g. a transformer including superconductors.

As the value of the critical current may vary along the conductor, it is of interest to determine the critical current along the superconductor in order to characterize the superconductor. It is of interest to perform the characterization of the conductor as a contact-less measurement as it enables a continuous determination of the critical current for a conductor over the entire length of the conductor. In addition, the contact-less measurement has the advantage of saving the conductor and the measurement means from wear due to mechanical contact.

A method and an apparatus for testing a conductor which consists at least partially of superconductive material is disclosed in US patent 3,976,934. The patent teaches that the testing of a conductor with superconductive material in the superconducting state can be performed by moving the conductor through an external magnetic field which induces shielding currents in the superconductor material and by measuring the magnetic field generated by these shielding currents. The critical current is determined using the measured shielding field.

The object of the invention is to provide a method for the determination of the critical current for a conductor including superconducting material, which method gives a better and more reliable determination than methods according to the prior art.

This object is achieved by performing the method as stated in the characterizing portion of claim 1.

According to the invention, the determination of the critical current for a conductor including superconducting material is performed using a method, wherein said conductor is brought into a superconducting state, and wherein a varying external magnetic field is generated,

through which said conductor is conveyed, and wherein a first measurement means is used to carry out a first contact-free measurement of the resulting magnetic field that occurs as a consequence of the influence of the con-

5 ductor by said external magnetic field. The part of the resulting magnetic field out of phase with the external magnetic field is determined, and the critical current of the conductor is determined on the basis thereof.

10 The method according to the invention is advantageous as it uses a so-called coupling of the filaments in a conductor having a multi-filament structure to obtain a larger signal to noise ratio for the measured signal due to the fact that the measurement is performed on all the

15 filaments in the conductor. The resulting magnetic field is larger when the filaments are coupled, as each filament hereby contributes constructively to the generation of the resulting magnetic field.

20 The method according to the invention is advantageous over prior art methods in which the resulting magnetic field, which reflects the value of the critical value, is relatively small due to field suppression. Due to field suppression, that the superconducting characteristics of

25 a superconductor are reduced when exposed to a external magnetic field. Field suppression results in a relatively small magnetic field which reflect the critical current which provides a relatively small signal to noise ratio in the measured signal.

30

Using a method according to the prior art, it is difficult to obtain an optimum magnetic field in practice as both a too small and a too large external magnetic field result in a magnetic field which is lower than the opti-

35 mum magnetic field. An optimum external field, when using a method according to the prior art, is a field that is

large enough to induce shielding currents in the entire cross-section of the superconductor material to reach the critical current density. As the value of an optimum external value typically varies along the conductor, the measured magnetic field will therefore reflect this unwanted effect. These difficulties are avoided when using a method according to the invention as that part of the resulting magnetic field which is out of phase with the external magnetic field is used to determine the critical current.

In a preferred embodiment, a second measurement is carried out on the resulting magnetic field from another side in relation to the conductor by using a second measurement means. This second measurement is performed in addition to said first measurement of the resulting magnetic field from a first side in relation to the conductor. On the basis of these measurements, a more reliable result can be obtained. It also permits a supervision of the measurement. For example, it is possible to determine the distance between the conductor and the measurement means, and hereby to supervise the conveyance of the conductor, and it is possible to observe differences between the measurements of the different measurement means, which can e.g. be caused by ice on the measurement means.

In a preferred embodiment, compensation is made for measurement variations that occur as a consequence of variations in distance between conductor and measurement means. This compensation is made on the basis of said first measurement, or any value derived therefrom, and on the basis of said second measurement, or any value derived therefrom.

It is particularly advantageous to perform said compensation by means of the formula $U=((A+B)-k(A-B)^2)/2$, wherein

a corrected field value U is determined on the basis of the value A that is the field value from said first measurement or a value derived therefrom, and on the basis of the value B that is the field value of said second meas-
5   urement or a value derived therefrom.

The invention also relates to an apparatus for the determination of the critical current for a conductor including a superconducting material adapted to perform the
10 method according to the invention.

The apparatus comprises a conveyor arranged to convey the conductor through the apparatus, a cryostat arranged to cool the conductor to make it assume a superconducting
15 state, a field generation device arranged to generate a varying magnetic field through which the conductor is conveyed, and a first measurement means arranged to carry out a measurement of the resulting magnetic field that occurs as a consequence of the influence of said magnetic
20 field on said conductor. The apparatus further comprises means arranged to determine, on the basis of the measured magnetic field, that part which is out of phase with the resulting magnetic field, and on the basis of this to determine the critical current of the conductor.
25
In a preferred embodiment of the invention the field generating device comprises Helmholtz coils.

In a preferred embodiment, said first measurement means
30 in the apparatus is arranged to carry out a measurement of the resulting magnetic field from a first side in relation to the conductor, and the apparatus further comprises a second measurement means arranged to carry out a measurement of the resulting magnetic field from another
35 side in relation to the conductor. This is advantageous as the apparatus can be used to perform a more reliable

measurement, and to supervise the measurement. Hereby it is possible to determine the distance between the conductor and the measurement means, and to supervise the conveyance of the conductor. By observing the measurements

5   from the different measurement means, it is also possible to determine the differences, which e.g. can be caused by ice on the measurement means.

The apparatus advantageously comprises compensating means

10 arranged to compensate, on the basis of measurements from said first and said second measurement means or values derived therefrom, for measurement variations due to the distance between conductor and measurement means.

15 Said compensating means is advantageously arranged to carry out said compensation by using the formula $U=((A+B)-k(A-B)^2)/2$, wherein a corrected field value U is determined on the basis of said measured field value A from said first measurement means or any value derived

20 therefrom, and on the basis of the measured field value B from said second measurement means or any value derived therefrom.

In a preferred embodiment, said cryostat comprises a me-

25 chanical control device for controlling the conveyance of the conductor through the cryostat, and said cryostat is arranged to contain a coolant for cooling the conductor.

In a preferred embodiment, the apparatus comprises two

30 separate guides between which the conductor is freely suspended, and said field generating device and measurement device are arranged between the two guides. This is advantageous as the cryostat does not include any movable parts. It is further advantageous as the cryostat does

35 not include components which could influence the measurements.

Said control device advantageously comprises two slide guides, which is advantageous due to the simple and hereby sturdy construction.

5

In a preferred embodiment of the apparatus said guides are made of high density polyethylene. This is advantageous as this material can withstand the influence from the environment.

10

The invention will be explained more fully by the following description with reference to the drawing, in which

fig. 1 is a side view of an apparatus according to the
15   present invention,

fig. 2 shows a section of the apparatus according to the invention from a second side,

20   fig. 3 illustrates the coupling of filaments in a conductor including superconducting material, and

fig. 4 illustrates the relationship between the shielding field and the external magnetic field, and the relation-
25   ship between the remanent field and the external magnetic field.

Fig. 1 shows a preferred embodiment of an apparatus according to the invention. The cryostat containing the
30   cooling medium 14 consists of a central vessel 9 and two tubes 7. A conductor 1 including superconducting material is conveyed from a coil 10 into the cryostat 7,9 through a field generating device 2, out of the cryostat and recoiled 11. The apparatus also comprises a mechanical con-
35   trol device which is designed to assure that the conductor movement in vertical and horizontal directions is re-

stricted and that the conductor is not exposed to bending radius smaller than a given value, e.g. 200 mm. The field generating device 2, which is also called the magnet 2 hereinafter, may be constructed as a pair of Helmholtz

5 coils. In the magnet 2 the field, B, is normal to the conductor surface and the field strength is advantageously high enough to obtain twice the field of full penetration for the actual superconductor. A first measurement means 5 and a second measurement means 6 are

10 placed above and below the tape respectively. The measurement means 5,6, which are also called magnetic sensors 5,6 hereinafter, may e.g. be Hall probes, inductance coils, or superconducting circuits (squids).

15 The mechanical control device comprises two slide guides 3,4, which is advantageous due to the simple and hereby sturdy construction. The conductor is freely suspended between the two slide guides which are separated. The field generating device and the measurement device are

20 arranged between the two guides. This is advantageous as the cryostat does not include any movable parts. It is further advantageous as the cryostat does not include components which could influence the performed measurements. The guides are made of high density polyethylene,

25 but can be made of other material if desired.

When the conductor 1 is conveyed through the apparapus, by using a conveyor (not shown), the conductor is conveyed through the cooling medium 14 and is hereby brought

30 into a superconducting state. The magnet 2 is adapted to generate a varying external magnetic field through which said conductor is conveyed. Hereby a magnetic field is generated. A first contact-free measurement of the resulting magnetic field that occurs as a consequence of

35 the influence of said external magnetic field on the conductor is carried out using the first measurement means

5. The resulting magnetic field is also measured from another side in relation to the conductor using the second measurement means 6. It is advantageous to perform both the first and the second measurement, as they result in a
5 more reliable measurement and make it possible to supervise the measurement, e.g. to determine the distance between the conductor and the measurement means, and hereby to supervise the conveyance of the conductor. It is also advantageous as it permits observation of differences be-
10 tween the measurements of the different measurement means 5,6, which can e.g. be caused by ice on the measurement means 5,6, or be caused by defects.

The resulting magnetic field is a sum of the external
15 field and the field induced by the superconductor, i.e. the so-called self-field. The self-field contains information about the superconducting properties of the tape. These properties are the critical current, the critical current distribution and density, distribution of induced
20 superconducting and non-superconducting currents, coupling of filaments, filament geometry, induced AC losses, field suppression, etc. All of these properties will influence the amplitude and time dependence of the self-field. It is noted that the frequency of the varying ex-
25 ternal magnetic field is given a certain high value in order to ensure coupling of all the filaments in the conductor 1.

It is determined on the basis of the measurement which
30 part of the resulting magnetic field is out of phase with the external magnetic field. The critical current is determined on the basis thereof. It is noted that the part of the measured magnetic field which is in phase and out of phase with the external field will be close to the
35 shielding field and the remanent field respectively and

are taken as the most important parameters describing the
superconducting properties of the conductor 1.

On basis of the first measurement, or any value derived
5   therefrom, and on the basis of said second measurement,
or any value derived therefrom, a compensation is made
for measurement variations that occur as a consequence of
variations in distance between conductor 1 and measure-
ment means 5,6. The compensation is e.g. performed by
10   means of the formula $U=((A+B)-k(A-B)^2)/2$, wherein a cor-
rected field value U is determined on the basis of the
value A that is the field value from said first measure-
ment or a value derived therefrom, and on the basis of
the value B that is the field value of said second meas-
15   urement or a value derived therefrom. It is noted, that k
is a constant having a given value, e.g. 0.42.

The method according to the invention is advantageous as
the coupling of the filaments in a conductor having a
20   multi-filament structure provides a larger signal to
noise ratio for the measured signal due to the fact that
the measurement is performed on all the filaments in the
conductor simultaneously. The resulting magnetic field is
larger when the filaments are coupled, which will be de-
25   scribed in the following.

Fig. 2 shows a section of the apparatus of fig. 1 from a
second side. The conveyer means 3 are designed to keep
the tape steady in horizontal as well as vertical direc-
30   tions.

The conductor 1, which comprises superconducting mate-
rial, is formed as a tape and includes a number of fila-
ments 8 arranged to form a multi-core conductor. The con-
35   ductor 1 is also called the tape 1 hereinafter, even
though the conductor can also be formed in other ways.

Each filament 8 comprises superconducting material and is typically enclosed by another material e.g. silver, in order to give a flexible structure. Different types of

5   superconducting materials are used, and can e.g. comprise Bismuth (Bi), Strontium (Sr), Calcium (Ca) and Copper (Cu) in a given ratio.

The filaments 8 in the tape 1 may be coupled due to the

10   time derivative of the external magnetic field. The effect of coupling is that the filaments appear as one superconductor, and this is illustrated by the field lines 20 representing the lines from a single superconductor.

15   Fig. 3 illustrates the importance of filament coupling. The figure shows the field above two tapes where the filaments are not coupled (left) and where the filaments are coupled (right). Coupling of filaments increases with the time derivative of the field and with the conductiv-

20   ity of the matrix material. Coupling of the filaments makes the superconducting currents couple together into one loop carrying the critical current. The magnetic field obtained by such a loop is much stronger than the field obtained by several loops. This is illustrated in

25   the figure by only two filaments. The effect increases with the number of filaments. When the filaments couple, the magnetic field is much bigger and more easy to measure and the relation between the measured field and the critical current is simple to calculate by using Biot-

30   Savart's law.

Fig. 4 illustrates the relationship between the shielding field and the external magnetic field, and the relationship between the remanent field and the external magnetic

35   field. The critical current carried by the superconductor depends on the amplitude of the external field. This is

due to the field suppression. The remanent field will increase with the external field until saturation occurs around twice the field of full penetration. Then the remanent field is saturated. The shielding field will start

5   decreasing at higher fields due to the field suppression. The remanent field is advantageously measured when the external field is zero, while the shielding field is advantageously measured while the external field is at its maximum value. The remanent field will be a measure of

10   the critical current at zero external field (self field).

Although a preferred embodiment of the present invention has been described and shown, the invention is not limited to it, but may also be embodied in other ways within

15   the scope of the subject-matter defined in the appended claims.

Patent Claims:
_____

1. A method for the determination of the critical current
5 for a conductor including superconducting material,
  — wherein said conductor is brought into a superconduct-
  ing state,
  — and wherein a varying external magnetic field is gen-
  erated through which said conductor is conveyed,
10 — and wherein a first measurement means is used to carry
  out a first contact-free measurement of the resulting
  magnetic field that occurs as a consequence of the influ-
  ence of said external magnetic field on the conductor,
  c h a r a c t e r i z e d   in that the part of the re-
15 sulting magnetic field out of phase with the external
  magnetic field is determined, and that the critical cur-
  rent of the conductor is determined on the basis thereof.

2. A method according to claim 1, c h a r a c t e r -
20 i z e d   in that in addition to said first measurement
  of the resulting magnetic field from a first side in re-
  lation to the conductor, a further, second measurement of
  the resulting magnetic field is carried out from another
  side in relation to the conductor using a second measure-
25 ment means.

3. A method according to claim 2, c h a r a c t e r -
  i z e d   in that on the basis of said first measurement,
  or any value derived therefrom, and on the basis of said
30 second measurement, or any value derived therefrom, com-
  pensation is made for measurement variations that occur
  as a consequence of variations in distance between con-
  ductor and measurement means.

35 4. A method according to claim 3, c h a r a c t e r -
  i z e d   in that said compensation is made by means of

the formula $U=((A+B)-k(A-B)^2)/2$, wherein a corrected field value U is determined on the basis of the value A that is the field value from said first measurement or a value derived therefrom, and on the basis of the value B

5   from that is the field value of said second measurement or a value derived therefrom.

5. An apparatus for the determination of the critical current for a conductor including a superconducting mate-

10   rial, wherein said apparatus comprises
- a conveyor arranged to convey the conductor through the apparatus
- a cryostat arranged to cool the conductor and to make it reach a superconducting state,

15   - a field generation device arranged to generate a vary-ing magnetic field through which the conductor is con-veyed, and
- a first measurement means arranged to carry out a meas-urement of the resulting magnetic field that occurs as a

20   consequence of the influence of said magnetic field on said conductor,
c h a r a c t e r i z e d   in that the apparatus further comprises means arranged to determine the part of the of the resulting magnetic field out of phase with the exter-

25   nal magnetic field, and on the basis of this to determine the critical current of the conductor.

6. An apparatus according to claim 5, c h a r a c -
t e r i z e d   in that the field generating device com-

30   prises Helmholtz coils.

7. An apparatus according to claim 5 or 6, c h a r a c -
t e r i z e d   in that said first measurement means is arranged to carry out a measurement of the resulting mag-

35   netic field from a first side in relation to the conduc-tor, and that the apparatus further comprises a second

measurement means arranged to carry out a measurement of the resulting magnetic field from another side in relation to the conductor.

8. An apparatus according to claim 7, c h a r a c - t e r i z e d by further comprising compensating means arranged to compensate, on the basis of measurements from said first and said second measurement means or values derived therefrom, for measurement variations due to the distance between conductor and measurement means.

9. An apparatus according to claim 8, c h a r a c - t e r i z e d in that said compensating means is arranged to carry out said compensation by using the formula $U=((A+B)-k(A-B)^2)/2$, wherein a corrected field value U is determined on the basis of said measured field value A from said first measurement means or any value derived therefrom, and on the basis of the measured field value B from said second measurement means or any value derived therefrom.

10. An apparatus according to one or more of claims 5-9, c h a r a c t e r i z e d in that said cryostat comprises a mechanical control device for controlling the conveyance of the conductor through the cryostat, and that said cryostat is arranged to contain a coolant for cooling the conductor.

11. An apparatus according to claim 10, c h a r a c - t e r i z e d in that said control device comprises two separate guides between which the conductor is freely suspended, and that said field generating device and measurement device are arranged between the two guides.

12. An apparatus according to claim 10 or 11, c h a r - a c t e r i z e d   in that said control device comprises two slide guides.

5   13. An apparatus according to claim 12, c h a r a c - t e r i z e d   in that said guides are made of high den- sity polyethylene.

A method for the determination of the critical current for a conductor including superconducting material, and an apparatus for performing the method

ABSTRACT

The invention relates to a method for the determination of the critical current for a conductor including super-conducting material. The conductor is brought into a superconducting state, and a varying external magnetic field is generated through which said conductor is conveyed. A first measurement means is used to carry out a first contact-free measurement of the resulting magnetic field that occurs as a consequence of the influence of said external magnetic field on the conductor. The part of the resulting magnetic field out of phase with the external magnetic field is determined, and the critical current of the conductor is determined on the basis thereof.

The invention further relates to an apparatus for performing the method.
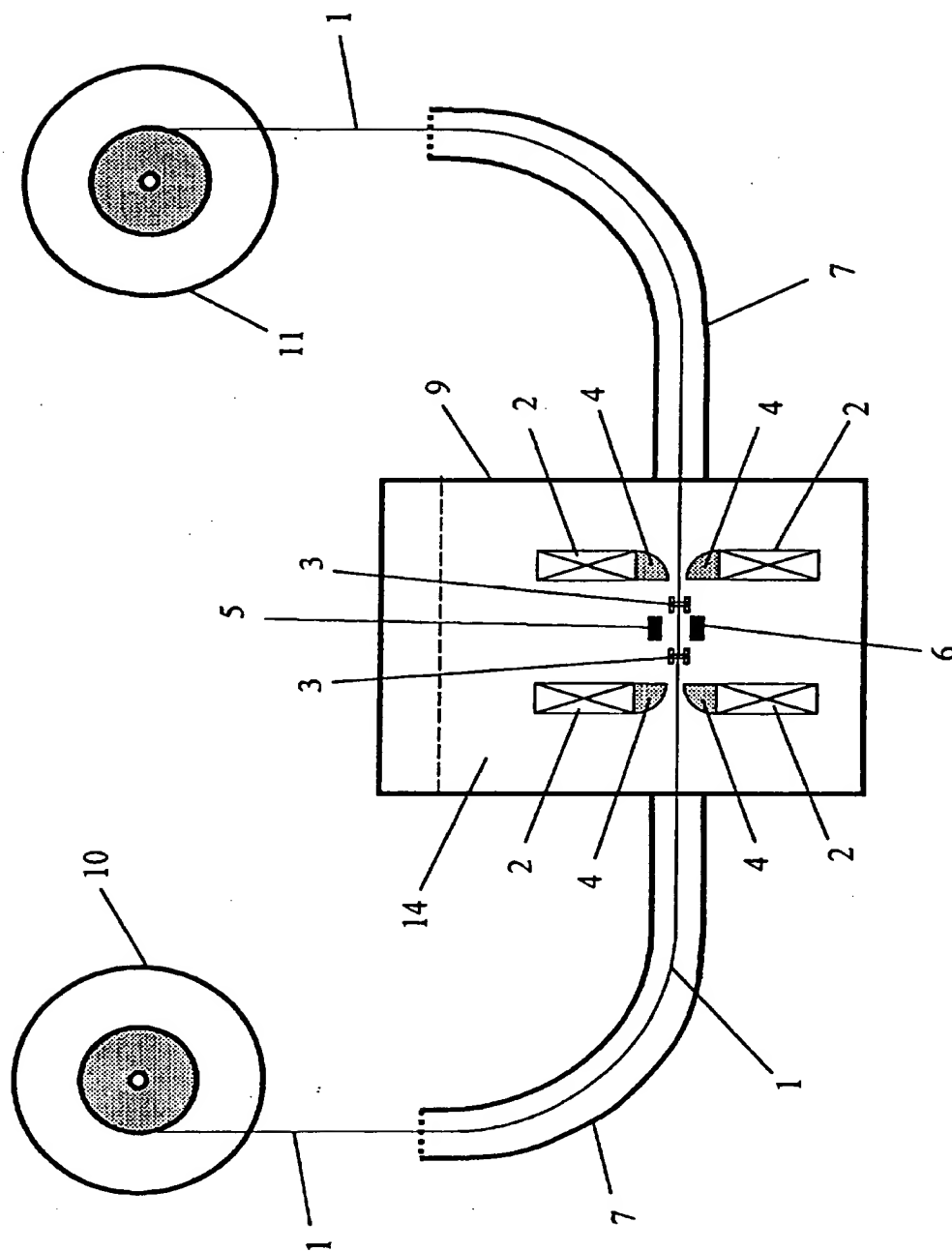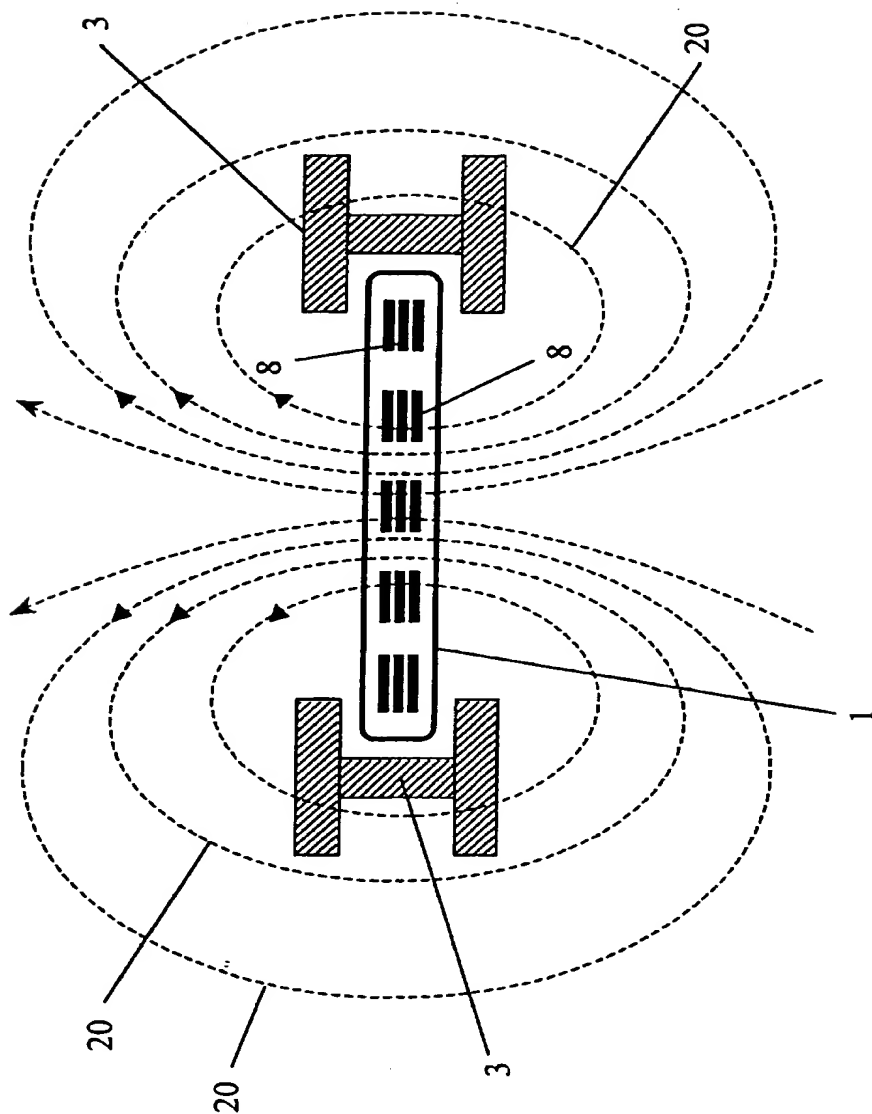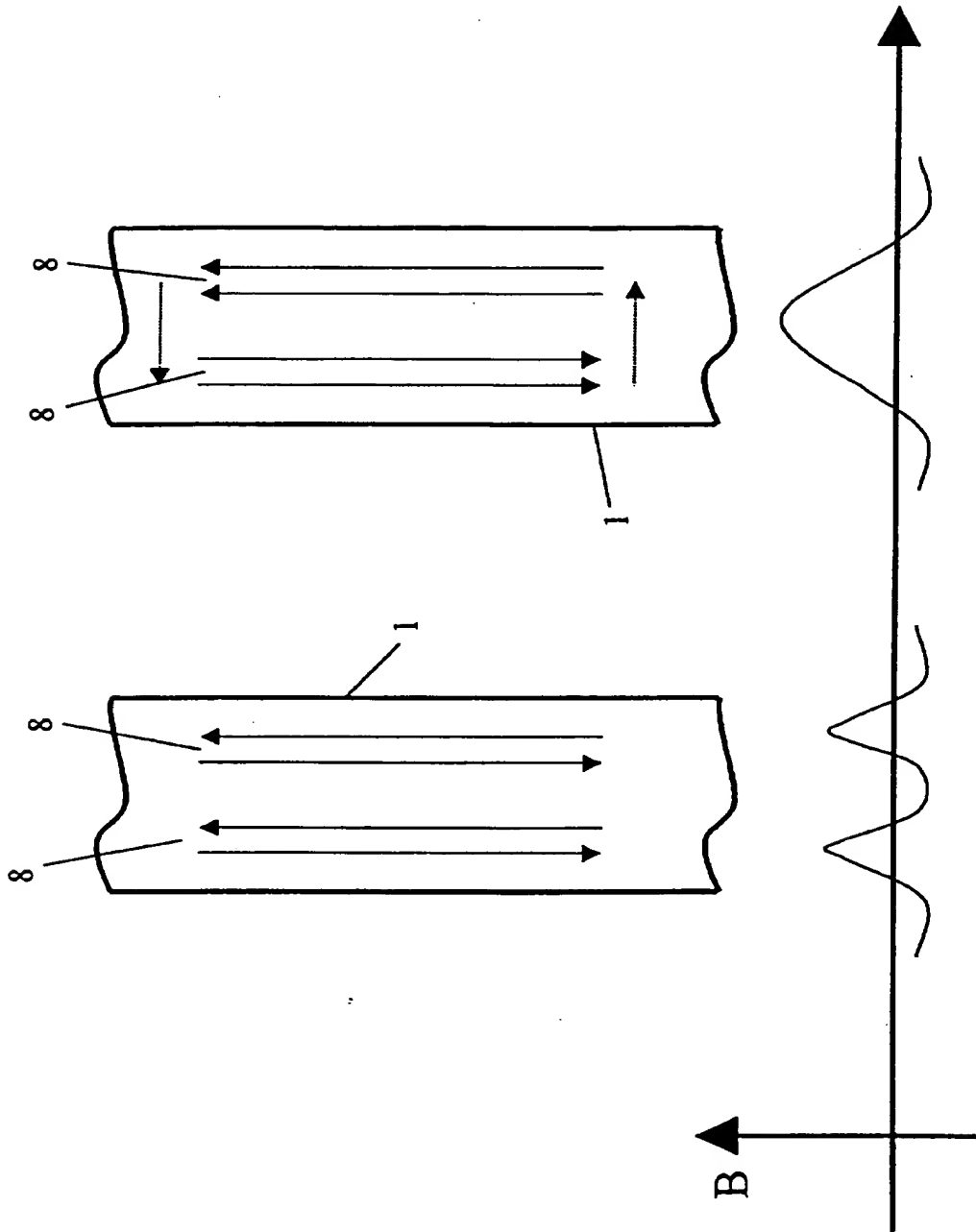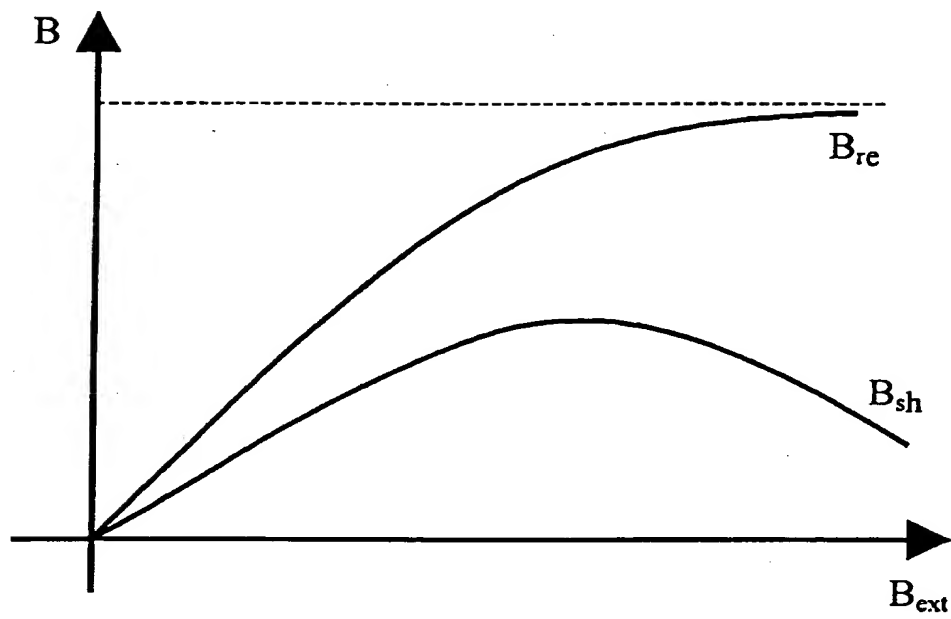
Fig. 1 should be published.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

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